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Birth of the Elements

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WHY do we think that the chemical elements were born at all, instead of having existed for an infinite length of time?

Physicists concluded early in this century that the elements must have had a start sometime, because a number of them are radioactive. This means that they decay into other elements which accumulate. Because we still see appreciable amounts of the radioactive parents, there would be an infinite pileup of their products if the universe were infinitely old. Actually, the quantity of decay products is limited, so we conclude that the elements were born at some point in time.

This argument can be made quantitative. We look at the amount of decay products existing in nature, measure the half-lives and abundances of the parent elements, and can tell how old the elements are. Calculations give from about five billion to 15 billion years, depending on whether the parents were made all at once and have been decaying ever since, or have been made gradually. We will see later in this article that the second interpretation seems better.

The first ideas about the origin of the chemical elements came from the findings of astronomical spectroscopists in the 19th century, when spectroscopy was new. They knew that if various substances were heated, the emitted light had certain characteristic wavelengths, which permitted identification of the component elements. The same spectrum lines that were seen in laboratory experiments could be found as absorption features in sunlight. Thus it was concluded that the elements in the sun were the same ones familiar on Earth. Today, about 70 of the elements that exist in nature have been identified on the sun. The rest are chiefly elements whose strongest lines lie in the far ultraviolet, outside the visual range. We may expect that spectroscopic observations from spacecraft will show that these missing elements also occur in the sun.

The exciting discovery that stellar spectra also showed lines familiar in laboratory experiments was a proof that the same chemical elements existed in the earth, sun, and stars. Modern observations have added the galaxies to this list. From these findings, it was natural to make the simplifying assumption that the composition of the universe is everywhere essentially the same.

Of course, the precise proportions of elements are not exactly the same in the sun and on the earth, because some gases that exist in the sun were largely lost from our planet when it was formed. Apart from such differences, the uniformity of composition in the cosmos is a good first guess.

The physical conditions during the early development of the universe hold the key to how the elements were made. As we shall see, nuclear reactions that make elements usually require exceedingly high temperatures. A few decades ago, this seemed to fit well with the idea that the universe is expanding. If there is such an expansion, some time far in the past everything must have been packed into a very dense, enormously hot mass, in which nuclear reactions could make elements.

From this basic picture have come several theories. One of them, called the equilibrium theory, says that, in the hot primitive material, the number of any type of atom being made was just balanced by the rate at which that kind of atom was being destroyed. Then some freezing-in process acted to halt the reactions, preserving the relative amounts of the elements.

These early ideas led to much interesting work, but this did not furnish precise predictions of element abundances. The deathblow to these ideas came with the realization, about a decade ago, that there are basic differences in composition among the stars. In other words, the composition of the universe is *not* everywhere the same.

The differences take two distinct forms. The first involves the abundance of heavy elements relative to hydrogen. Some stars seem to be almost pure hydrogen, much more nearly so than the sun. In these stars, the ratio of all the other elements to hydrogen may be a hundred times less than in the sun. These metal-deficient stars are very old ones.

This suggested the hypothesis that the galaxy once consisted entirely of hydrogen. Then, nuclear reactions in stellar interiors began. When these stars ejected material or blew up as supernovae, the products of the nuclear reactions would be spread into interstellar space, mixing with the hydrogen already there. New generations of stars formed out of interstellar gas would generate still more of the heavy elements, and eventually add them to the interstellar medium. (This cyclic process would apply primarily to massive stars, as their evolution is much faster than for stars of low mass.)

The second kind of difference in composition involves only a few elements. For example, a star may be quite like the sun, except for a much greater abundance
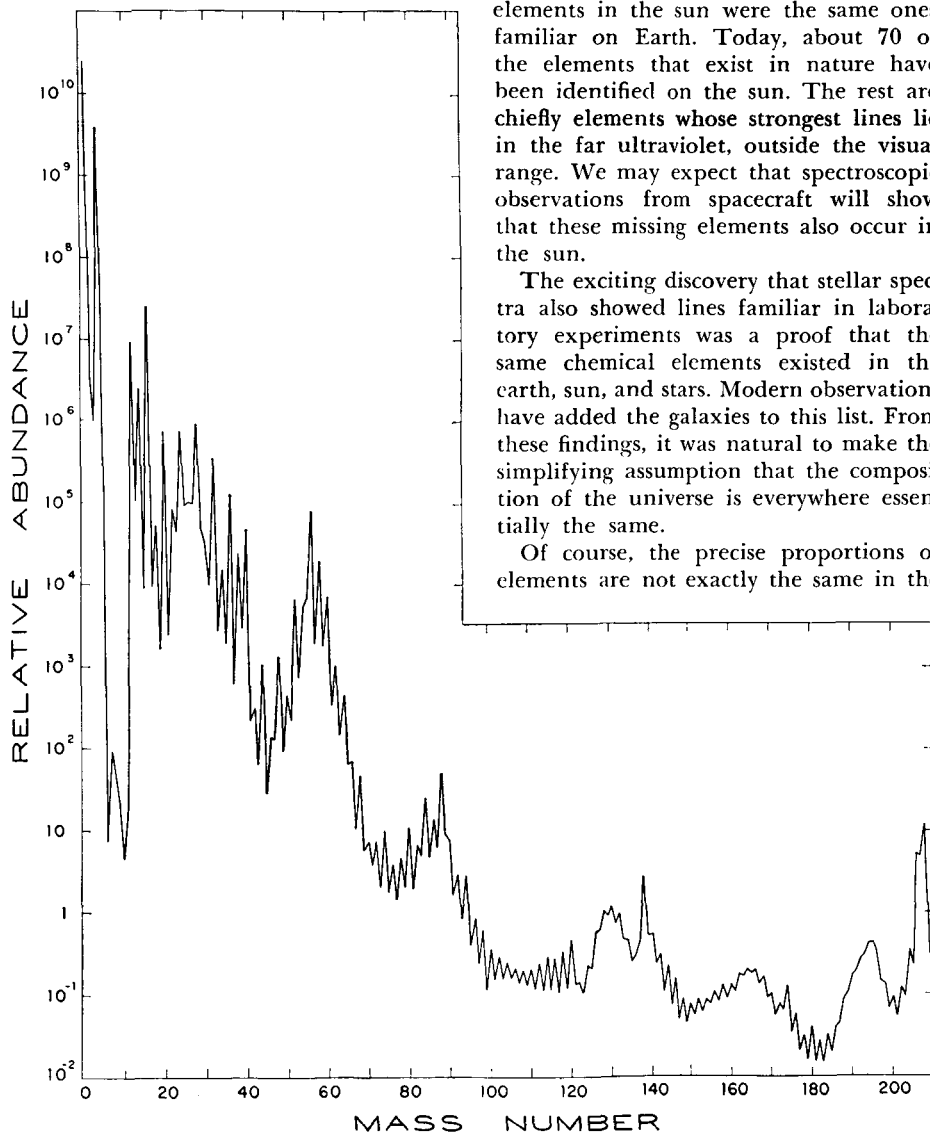

Fig. 1. In this chart, the relative abundances of the elements are plotted against mass numbers (the number of protons plus neutrons in each nucleus). Unless otherwise noted, diagrams with this article are by the author.

— 1 —

of carbon, or perhaps of all of the heavy elements beyond iron. Here we can recognize varied kinds of nuclear reactions going on in stellar interiors, building up the heavier elements in certain specific ways.

These two sorts of differences between stars have led to the newer view that the heavier elements have all been made by nuclear reactions inside stars, as a natural consequence of stellar evolution.

PROTON – PROTON CHAINS

$$H^1(p,\beta^+\nu)D^2(p,\gamma)He^3(He^3,2p)He^4$$
$$(\alpha,\gamma)Be^7(e^-,\nu)Li^7(p,\alpha)He^4$$
$$(p,\gamma)B^8(\beta^+\nu)Be^8(\alpha)He^4$$

Fig. 2. Proton-proton reactions provide one of the ways that four protons can combine to form a helium nucleus.

Mention should be made of two other theories, one proposed by Maria Mayer and Edward Teller, the other by R. A. Alpher, G. Gamow, and H. A. Bethe. In the former, it was suggested that during the early stages of the universe there existed large bodies composed of neutrons. These bodies would continually divide, throwing off matter which would later decay to become the nuclei of atoms. This idea interested physicists and influenced later thinking.

The Alpher-Gamow-Bethe proposal had a good deal of support until about a decade ago. It was called the big-bang theory, referring to the initial explosion of the universe. This postulated that the universe in its first half hour was at very high temperature and density, with all matter in the form of individual neutrons. Some of them later decayed to form protons, and these started capturing the remaining neutrons, in this way building up all the heavier elements. The theory had one major drawback — there is no stable nucleus of mass five. Successive reactions between neutrons and protons will form a deuteron of mass two, a triton of mass three, and a helium-4 (He⁴) nucleus. But there the process ends.

Therefore, let us look more closely into the theory that there has been a gradual building up of the heavier elements by nuclear reactions in stellar interiors. A good deal of insight into the manner in which this happens can be gained from Fig. 1. It is an abundance diagram of nuclei, rather than elements. There are some 90 elements in nature and more have been made artificially, but many are mixtures of various isotopes, which have a differing number of neutrons. It is much more instructive, in considering nuclear reactions, to plot the abundance of each mass number (the number of protons plus neutrons) rather than the abundance of each element.

The striking pattern in Fig. 1 is the result of enormous labor by many chemists, physicists, and astrophysicists. Abundances of the lighter elements can be measured spectroscopically in stars to a

factor of two, and the accuracy is still less for all the heavier elements. Valuable information has come from chemical and radiochemical studies of certain types of meteorites. The diagram is a composite of information from the stars and meteorites, helped by a good deal of hindsight from the theory of nuclear synthesis.

The most abundant nucleus in the universe is hydrogen, followed by helium. The next few elements — lithium, beryllium, boron — are far scarcer because, as we shall see, they are not products of the normal chain of nuclear reactions inside stars. Carbon, nitrogen, and oxygen are again very abundant, and the next elements are nearly as common — neon, magnesium, silicon, sulfur, argon, calcium. Then the curve plunges down, to rise again to another great peak centered on iron-56 (Fe⁵⁶). Beyond mass number 90 or 100 the level is more nearly constant, with a few sharp peaks superimposed.

Fig. 3. The carbon cycle, shown here in detail, is more complex than proton-proton reactions and takes place at somewhat higher temperatures.

These peaks imply a good deal to the nuclear physicist, for they occur at mass numbers where the elements find it difficult to capture neutrons. In a process where successively heavier nuclei are being built up by one neutron capture after another, these peaks represent the bottlenecks where elements accumulate. The nuclear physicist notes that some of the peaks occur in regions of nuclei where neutron capture is slower than most radioactive disintegrations (beta decays), and other peaks occur in regions of nuclei which can only be reached if the neutron capture is faster than beta decays. Hence there must be both fast and slow time scales for the neutron capture processes needed to make the heaviest elements.

By looking at the gross features of the abundance diagram, physicists can decide which nuclear processes have been at

work. Many different ones are needed. Making the large amount of helium, making the carbon-nitrogen-oxygen group, making the elements from magnesium up to calcium — all require separate processes. Many of the minor features involve special reactions. Indeed, we must consider a complicated superposition of many reactions that take place at different times in the evolution of the star.

Nowadays it is generally agreed among astronomers that stars contract from the interstellar medium (SKY AND TELESCOPE, December, 1962, page 328). The energy gained when a star shrinks is more than enough to support the outer layers. Part of the energy is stored, part radiated away. As the interior grows hotter, the lighter nuclei bombard one another energetically enough to fuse together in thermonuclear reactions. This supplies energy to radiate, and stops further contraction of the star for a considerable length of time, until the nuclear fuel is exhausted. Then the shrinking starts again, and the star's central temperature rises until the "ashes" of the first set of reactions can themselves react and generate more heat. This again stops the shrinkage while the new fuel is being exhausted. Then another contraction sets in; the whole pattern may repeat a number of times.
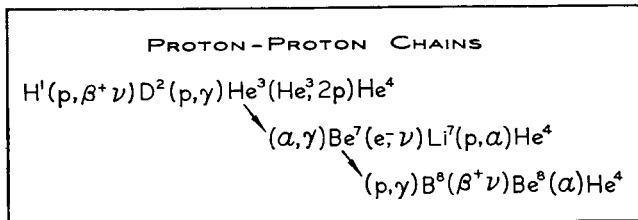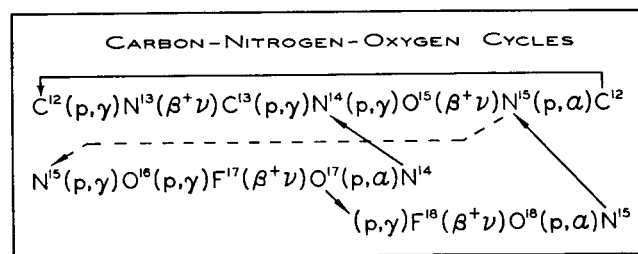
CARBON – NITROGEN – OXYGEN CYCLES

$$C^{12}(p,\gamma)N^{13}(\beta^+\nu)C^{13}(p,\gamma)N^{14}(p,\gamma)O^{15}(\beta^+\nu)N^{15}(p,\alpha)C^{12}$$
$$N^{15}(p,\gamma)O^{16}(p,\gamma)F^{17}(\beta^+\nu)O^{17}(p,\alpha)N^{14}$$
$$(p,\gamma)F^{18}(\beta^+\nu)O^{18}(p,\alpha)N^{15}$$

There are several ways in which hydrogen is converted to helium. In Fig. 2, a collision adds a proton p to a hydrogen nucleus H¹, causing a beta-decay process in which a positron and a neutrino are emitted, leaving a nucleus of deuterium (hydrogen of mass 2). This reaction is expressed by the formula

$$H^1 + p \rightarrow D^2 + \beta^+ + \nu,$$

which can be written more concisely as

$$H^1 (p, \beta^+ \nu) D^2.$$

In turn, the deuterium can capture another proton and emit a gamma ray to make helium-3 (He³). After a certain concentration of He³ has built up in the star, these nuclei can react with one another to release two protons and make He⁴. This may also be made in other ways. For example, if there already is some He⁴ in the star, it can interact with

CARBON REACTIONS

$$C^{12} + C^{12} \longrightarrow Na^{23} + p$$
$$\searrow Ne^{20} + \alpha$$

$$C^{12} + p \longrightarrow N^{13} (\beta^+\nu)C^{13}$$
$$C^{13} + \alpha \longrightarrow O^{16} + n$$
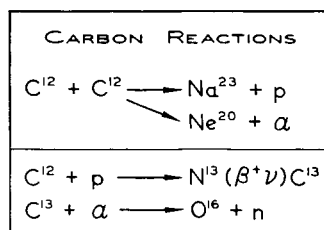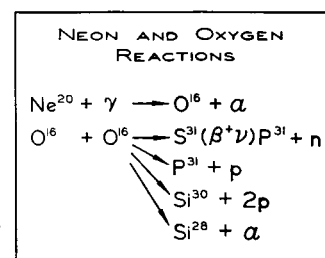
Fig. 4 (left). These carbon reactions produce some heavier elements.

Fig. 5 (right). Neon and oxygen are stepping-stones to still heavier atomic nuclei.

NEON AND OXYGEN REACTIONS

$$Ne^{20} + \gamma \longrightarrow O^{16} + \alpha$$
$$O^{16} + O^{16} \longrightarrow S^{31}(\beta^+\nu)P^{31} + n$$
$$\searrow P^{31} + p$$
$$\searrow Si^{30} + 2p$$
$$\searrow Si^{28} + \alpha$$

Fig. 6. If the right physical conditions exist, any one of the stable isotopes (indicated by black dots) can be transmuted to some other isotope that is connected to it by one of the lines. The particles involved in each reaction are given in the key at lower right. For example, the nickel-62 nucleus with 28 protons and 34 neutrons can be hit by a gamma ray, emit an alpha particle and become iron-58 with 26 protons and 32 neutrons. Running diagonally up the chart, for convenience in identifying the various isotopes, are mass numbers.

He^3 to emit a gamma ray and form Be^7 (beryllium). This in turn reacts with a proton to produce *two* He^4 nuclei (alpha particles).

If initially the star contains some carbon, nitrogen, and oxygen, then hydrogen can be converted to helium, as in Fig. 3. Carbon-12 (C^{12}) captures a proton to form radioactive nitrogen-13 (N^{13}), which releases a positron and a neutrino to make C^{13}. This in turn captures a proton to yield N^{14}, and another to make radioactive oxygen, O^{15}, which decays to N^{15}. This may capture another proton and emit a gamma ray, making O^{16}, but is more likely to emit an alpha particle. In other words, we have converted four protons into helium, and have got the C^{12} back. Some side chains and other possibilities complicate this carbon cycle, without changing it basically.

If a star has more than about the mass of the sun, eventually it stops converting hydrogen to helium near its center. Then the central temperature goes up, and the helium itself can begin to react.

Should two He^4 nuclei be joined together, a Be^8 nucleus would be expected, but it is not found in nature. It breaks up very rapidly into two helium nuclei.

Thus, little happens until the temperature grows so high that three helium nuclei join to form C^{12}. This jump from element number 2 to 6 means bypassing lithium, beryllium, and boron, which we saw from Fig. 1 are of very low abundance in the natural mixture of the elements.

The carbon formed can capture another helium nucleus to manufacture O^{16}, which is very abundant in nature. As the star's center grows hotter, carbon can combine with itself (Fig. 4).

A temperature of about 15 or 20 million degrees is needed to convert hydrogen into helium; about 100 million to convert helium into carbon and oxygen; and about 700 million degrees for carbon to react with itself.

When the star has evolved this far, a very interesting set of things happens. Combining two carbon nuclei can release a proton or an alpha particle. At the very high temperatures involved, these can rapidly react with anything available in the interior of the star, even with carbon itself. Another set of reactions generates neutrons. Quite a number of products are obtained, particularly in the region around neon-20 to magnesium-24.

As the temperature inside the star

climbs still higher, to around $1\frac{1}{2}$ billion degrees, gamma rays start reacting with Ne^{20}, breaking it down to O^{16} and an alpha particle (Fig. 5). O^{16} can react with itself to form a wide variety of products — neutrons, protons, and alpha particles included. The result is a very complex range of nuclei, mostly near silicon-28.

Beyond Si^{28} things become even more complex. Fig. 6 is a chart showing various nuclei, with the vertical scale indicating the number of protons in each, the horizontal scale the number of neutrons. Dark dots show naturally occurring nuclei, open circles unstable ones that do not exist in nature.

In this diagram, Si^{28} is represented by a black dot. When the temperature is raised to a few billion degrees, some Si^{28} is disrupted by high-energy protons to make Mg^{24}, which in turn is broken down to Ne^{20}, and so on, each step giving another alpha particle.

These alpha particles will be captured by other nuclei, Si^{28} thus being converted to sulfur-32 and this becoming argon-36. One complication: Such nuclei can be split by high-energy gamma rays, releasing neutrons and protons that can be re-

— 3 —

captured in a great variety of reactions. Actually, about half the Si^{28} nuclei break down into lighter particles that are captured by the remaining Si^{28} nuclei. Following some combination of the large number of reaction paths, the latter nuclei eventually reach the region of Fe^{56}. Iron will grow more abundant than any of its neighbors, because it is a particularly stable nucleus.

Energy can be released by fusing light nuclei together, or by the fission of very heavy ones. Somewhere between, there is a place at which the nuclei are as compact as possible in terms of energy. This is at Fe^{56}. Such nuclei are, of course, still being rapidly broken down by energetic gamma rays, but the products are recaptured to achieve a steady-state abundance. This abundance distribution is seen in Fig. 7, a diagram published several years ago by E. M. and G. R. Burbidge, W. A. Fowler, and F. Hoyle.

It compares the calculated relative abundances of elements with those observed in the sun. To interpret the solar observations, it was assumed that within each element the proportions of isotopes were the same as measured on Earth. There is a pretty good fit. The iron peak is one of the main products of nuclear reactions in stellar interiors — the end result of a long evolutionary sequence in which nuclei have gradually been milked of all their available energy.

Where do the still heavier elements come from? The star has continued shrinking and heating up in its interior, and the contraction has stopped at various stages when nuclear reactions provided energy to be radiated from the star. Finally, there is nothing to stop the contraction. It will go on, and the temperature will continue to rise. High-energy gamma rays increase more and more, breaking down nuclei, until the

most abundant kind will be not Fe^{56} but He^4! In other words, the iron nuclei traverse a long, complicated path down Fig. 6. The star's composition had changed from alpha particles to iron while it radiated energy; now it is changing from iron back to alpha particles. Where will the star get the energy? Only from shrinkage, which must be very rapid, for the transformation from iron back to helium takes place rather sharply at a given temperature and density. In fact, the star must collapse so rapidly that the energy released blows most of its mass away into space in a supernova explosion.
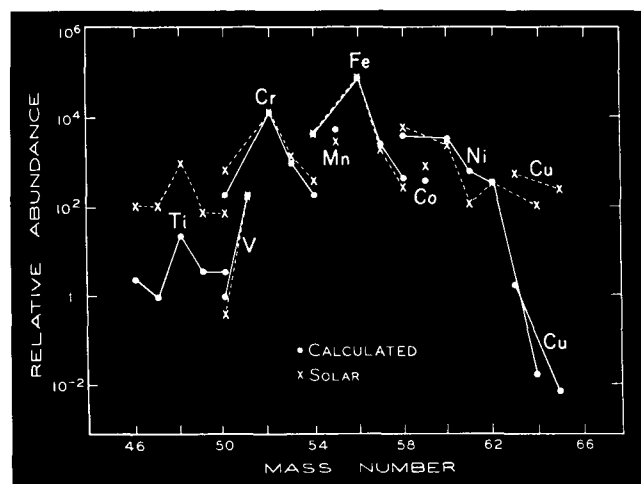
Take one more look at the star before it explodes. From the center outward, its temperature steadily decreases to a mere few thousand degrees at the surface. Along this temperature range are all the stages of nuclear transformation — unchanged hydrogen at the surface; then helium and the carbon-oxygen group; at deeper levels elements like magnesium and silicon; still lower, iron; and at the center iron has been destroyed. The supernova explosion blows all these various layers into space, adding the mixture

of elements to the interstellar medium. As the shock wave rips off the outer layers of the star, other minor reactions can take place, producing heavier elements.

There are many quantitative checks on our calculations of the abundances of various nuclei produced by nuclear reactions. We can measure abundances in meteorites and the stars, and isotope ratios in the laboratory. There are many striking agreements, as in Fig. 7, that give confidence we understand something about the basic nuclear processes, and their occurrence in the normal course of stellar evolution. Of course many problems are still unsolved, but they are mainly concerned with fitting known nuclear processes into the very complicated histories of stars. It is hard to tell which types of star are involved, or give details of how stars of different mass affect the composition of the interstellar medium. But we do feel that these nuclear reactions supply a basically correct overall picture of the birth of the elements.

Fig. 7. In addition to showing the good agreement between observed and theoretically calculated elemental abundances, this plot shows the relative peak at Fe^{56}. Diagram adapted from one by E. M. and G. R. Burbidge, W. A. Fowler, and F. Hoyle.